ADVANCED SEISMIC TESTING USING THE MULTI-AXIAL TESTING SYSTEM (MATS) IN NCREE

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ABSTRACT

Multi-Axial Testing System (MATS) is a 6-DOF loading system for advanced seismic testing of structural components or sub-assemblies in the NCREE. The MATS consists of two post-tensioned A-shape reinforced concrete frames interconnected by a steel-and-concrete composite cross beam and a reinforced concrete reacting base. The specimen can be anchored between the top cross beam and the bottom platen within a 5-meter high and 3.25-meter wide clear space. This paper describes the specifications of the force, velocity and displacement capabilities of the MATS. In additional, a number of tests recently conducted using the MATS. It includes the viscous damping wall, LRB base isolator, buckling restrained brace and a 40% reduced-scale bottom two and half stories coupled steel plate shear wall (C-SPSW) substructure. Although the pitch force control mode is not available on the MATS, the C-SPSW test results confirmed that this mode of control could be satisfactorily applied using the software developed for the Shared Common Random Access Memory Network (SCRAMNet) while the specimen was loaded using lateral displacement control mode. It is illustrated that the MATS is an effective facility for advanced hybrid seismic simulation.

INTRODUCTION OF MATS

The 6-DOF testing system "MATS" was completed in NCREE in 2008. Figure 1 shows the overview of the MATS. It includes a steel-and-concrete composite platen, two A-shape post-tensioned reinforced concrete frames (A-frames) and various kinds of servo-controlled hydraulic actuators. Figure 2 illustrates the six degrees of freedom (DOF) adopted for the platen. The 2.54-meter wide and 6.7-meter long platen is attached to seven vertical actuators from the bottom, two lateral actuators at each lateral side and two hold-down actuators on the top. The longitudinal actuators can be re-configured by using one or several dynamic or static actuators to meet different kinds of test requirements. The vertical, pitch and roll DOF of the platen can be controlled by the seven actuators in the bottom. The lateral and yaw DOF can be operated by the lateral actuators. With these actuators, the specimen in the MATS can be subjected to a combination of bi-directional shear forces, bi-directional bending moments and vertical load. The platen was fabricated by using 50-mm and 60-mm steel plates to form a box shape. The box was stiffened by welding three steel tee sections onto the bottom plate. The bottom and top plates were tied together by using 80-mm diameter steel rods uniformly spaced in longitudinal and

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lateral direction. The box was infill with 56-Mpa high strength concrete to enhance its stiffness and strength. The concrete strength in the two A-frames, reinforced concrete reacting base (RC-base), and cross beam was 70-Mpa. There are two post-tensioned parts interconnecting the two vertical columns and one cap beam in each A-frame. First, each RC-column was post-tensioned with 33.6MN to interconnect the cap beam and the RC-base. Then, the top cap beam in each A-frame was post-tensioned with 16MN to tie the two RC-columns together. The cross beam is a box girder stiffened with vertical stiffeners. There are built-in tie-down holes through the cross beam to allow anchoring RC or steel shim blocks for meeting the specimen height. The finite element analytical results suggest that the maximum deflection of the platen and the cross beam under a 60-MN vertical force is about 2mm (Lin & Tsai 2007).

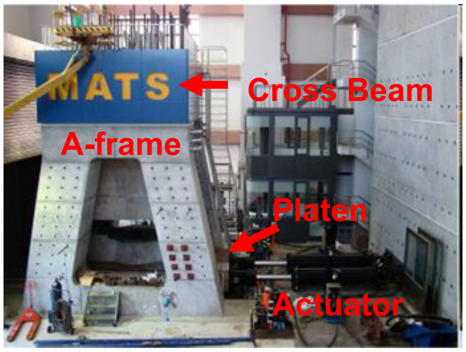

Fig. 1. MATS setup

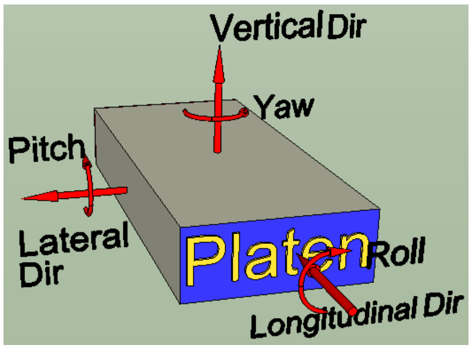

Fig. 2. Definition of each direction

FORCE, VELOCITY AND DISPLACEMENT CAPACITIES OF THE MATS

The MATS actuators work more effectively when the boost pump increases the oil pressure from 3,000psi to 4,000psi. The full capacities of MATS in each DOF are shown in Table 1. The detailed force or displacement specification in each DOF is given below.

Longitudinal Direction:

Currently, there are two configurations available. In Configuration 1, two static actuators are arranged in parallel. The stroke is ±1,200mm. The peak velocity is 30mm/sec. The maximum forces are 4.4MN in pushing and 3.54MN in pulling. In Configuration 2, two dynamic actuators are adopted to replace the two static ones. The stroke capacity is ±500mm. The maximum velocity is 600mm/sec. The force capacity is ±2MN.

Lateral Direction:

There are four static actuators symmetrically placed at two lateral sides of the platen as shown in Fig. 3. The four lateral actuators are the single-end pancake type with pressure balanced bearing at the interface to the platen. The range of the stroke is ±100mm. The maximum pushing force of each actuator is 2MN. Therefore, the overall lateral force capacity of the system is slightly less than ±4MN. The maximum velocity can reach up to 20mm/sec.

Vertical Direction:

The vertical actuators shown in Fig 3 can be divided into the bottom and the top parts. The bottom actuators include one central static and six side dynamic actuators. The static actuator is a single-end pancake type actuator with the pressure balanced type bearing at the interface to the platen. The capacity of this static actuator is 30MN, which is measured by the pressure transducer (delta-p cell). The six dynamic actuators are the single-end pancake type actuators with hydrostatic bearings at the interface to the platen. Actuator displacement is measured by a Temposonic transducer and force is measured by a delta-p cell. The full capacity of each dynamic actuator is 5MN. Therefore, the total vertical pushup force capacity can reach 60MN. The central 30-MN static actuator is turned on only when the vertical force requirement is greater than 30MN. The six side dynamic actuators can be operated independently without turning on the central static actuator. In this manner, without the use of the central static actuator, the maximum velocity can be increased from 10mm/sec to 60mm/sec. It should be noted that when any one of these actuators is used, it must be always in contact with the bottom of the platen. For this reason, additional two top hold-down actuators are built-in to allow a peak of 4MN compressive force to be applied on the top surface of the platen to ensure the bottom actuators can meet the minimum compression force requirements. The two hold-down actuators are also single-end pancake type with pressure balanced bearings at the interface to the platen.

Roll, Pitch And Yaw Directions:

For these three DOF, the maximum rotational capacity is ±2° based on the front end rotational capacity of the vertical and lateral actuators. The velocity capability in the roll and pitch DOF can reach up to 0.05rad/sec. Although delta-p cells are used for force measurements, force control mode is not directly provided by the manufactory. However, force control can be performed by using a Simulink model with the SCRAMNet interface. The example implementation is introduced in the C-SPSW cyclic test later in this paper.

Table 1. MATS capacity

DOF	Type	Stroke	Velocity	Force
Longitudinal	Static	±1,200mm	±30mm/sec	+4.4MN ; -3.54MN
	Dynamic	±500mm	±600mm/sec	±2MN
Lateral	Static	±100mm	±20mm/sec	±4MN
Vertical	Dynamic	+150mm	±60mm/sec	+30MN
	Static	+150mm	±10mm/sec	+60MN
Roll	Dynamic	±2°	±0.06rad/sec	±8MN-meter
Pitch	Dynamic	±2°	±0.05rad/sec	±27MN-meter
Yaw	Static	±2°	±0.015rad/sec	±5.61MN-meter
Symbol "+" points to the direction given in Figure 2.				

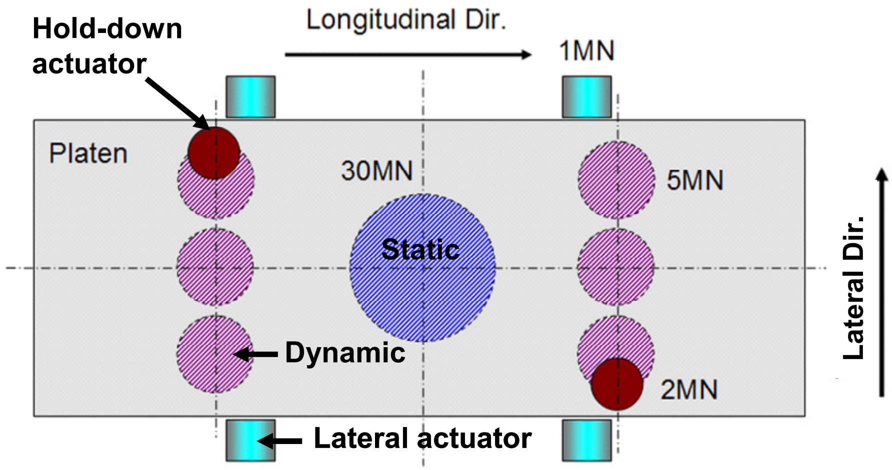

Fig. 3. Various actuators for the platen
(7 actuators represented by dotted lines are below the platen)

CONTROL SYSTEM OF MATS

All DOF can be directly controlled by using the Jacobean-matrix transformation calculated from the feedback of actuators. In light of the limited functions about the MATS host PC and the MATS controller, the SCRAMNet interface is adopted to set up a more versatile control system. The features implemented on the SCRAMNet interface such as the hold function or control-mode setups are available for the various testing needs. Figure 4 shows the framework of the MATS control system. The system can be divided into two major bodies: (1) the MATS controller and the host PC and (2) the SCRAMNet interface. On the MATS host PC, the MATS Control Panel is the control software which allows the assignments of the control gains and the control function. The Shared Common Random Access Memory Network (SCRAMNet) interface can be used to conduct hybrid testing when the MATS Control Panel is switched to the SCRAMNet mode. The SCRAMNet interface includes the "host PC" and the "Target PC" which works under the real-time operating system created by the Simulink. There are two SCRAMNet cards designated for hybrid testing, one of which is installed in the MATS controller and the other one is in the aforementioned Target PC. These two cards are digitally-interconnected using fiber optical cables. The Real-time Workspace toolkit is utilized to build the Simulink networking model. It is then transformed into C-code by using the C-compiler in the Simulink before it is infixed into the Target PC. With SCRAMNet interface, the commands generated by the Target PC and the feedback sent to the MATS controller are simultaneously stored on the SCRAMNet card. The stored data can be analyzed or processed using the Simulink model. Any subsequent commands generated from the Simulink model can be sent to the MATS controller to form a closed-loop control. With the programming flexibility of the Simulink and the high-speed performance of the SCRAMNet interface, the entire MATS control system can be constructed to carry out advanced hybrid tests. Similar techniques have been applied in the past few years (Shing *et al.*, 2004; Chu *et al.*, 2006) in earthquake engineering simulations. Limited experimental data can be recorded by using the Data Recorder in the MATS Control Panel using a sampling rate from 32Hz up to 1,024Hz. However, additional data acquisition (DAQ) system is necessary if more experimental data are required. This separate DAQ system can be run independently or triggered by the MATS controller using the SCRAMNet interface to synchronize with the Simulink-based model.

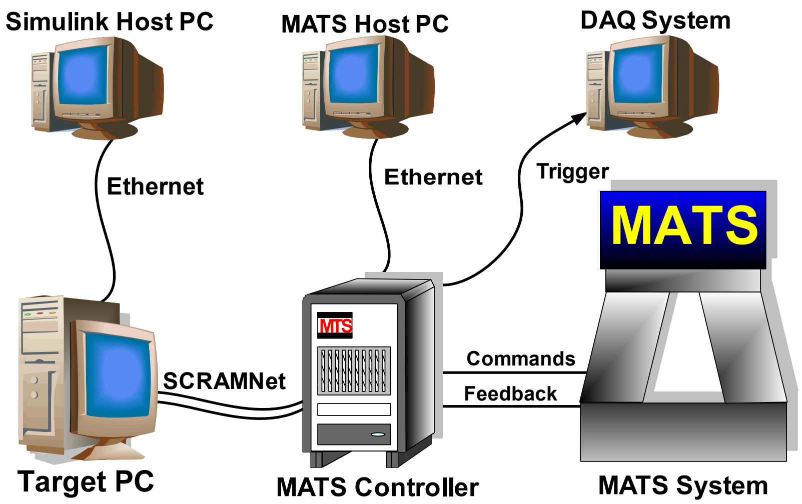

Fig. 4. Framework of the MATS control system

EXAMPLE EXPERIMENTS

This section introduces several tests conducted recently on MATS according to their complexity. First, tests of a viscous damping wall and a LRB base isolator using the MATS Control Panel are introduced. Second, the application of SCRAMNet interface with a Simulink based model for testing of a buckling restrained brace test is described. Finally, the cyclic test of a C-SPSW is illustrated using the Pitch Force Control model implemented in Simulink.

Viscous damping wall and LRB

The setups for tests of viscous damping wall and a LRB are shown in Fig. 5. The RC shim blocks or the steel reaction beams were used to adjust the position of the test specimens. These specimens were placed vertically and anchored between the RC blocks and the platen. For both tests, the longitudinal displacement commands of the sine-wave loading were generated by the MATS Control Panel. For the viscous damping walls tests, the vertical displacement was kept in constant during the test. As for the LRB tests, several constant vertical loads were applied according to the seismic building code requirements in Taiwan. Figure 6 shows the shear force versus shear deformation relationships of these two specimens. The peak shear forces of the viscous damping wall and the LRB are about 250kN and 1,800kN, respectively.

Fig. 5. Test setups for (a) a viscous damping wall and (b) a LRB

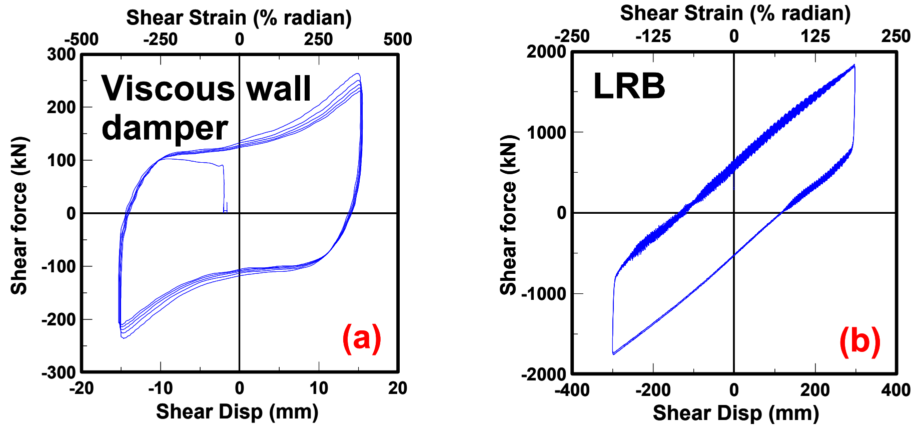

Fig. 6. Force versus deformation relationships for (a) the viscous damping wall (b) the LRB

Buckling restrained brace

Figure 7 shows the test setup of the buckling restrained brace (BRB) placed between the two longitudinal actuators. Due to the testing requirements for the hold (for observations) and trigger functions (for data acquisition for specific displacement steps), the development of a loading command model using Simulink was needed. This model (Fig. 8) was to provide the commands on the longitudinal DOF, or give an axial cyclic loading on the specimen. In this model, the Input form SCRAMNet block was for receiving signals from the MATS controller and the Output to SCRAMNet block was for sending signals to MATS controller. All forces or displacements generated in the Simulink model are considered as the relative commands for MATS. Before the end to the test, if the control mode were directly switched back to the MATS Control Panel, the discontinuity of the commands would result in sudden movement of actuator which would be highly likely to cause damage to the equipment or specimen. Therefore, the Stopper block has been applied to allow adjustments from 100% (during the test) to 0.0 (before ending the test) to ensure a full and zero displacement commands, respectively. Additionally, the Authority block has been the safeguard to avoid unexpected commands. The Target Scope block can display an oscilloscope on the screen of the Target PC when the model is running. The loading protocol (Fig. 9) can be prescribed using the Loading Command block. Equation 1 has been incorporated implemented into the control algorithm, logic analysis and hold or trigger functions by using the Simulink embedded function in the Loading Command block.

$$D_{n+1} = D_n + (H \times r \times dt \times T) \quad \text{.....................................} \quad (1)$$

Where D_n is the current displacement, D_{n+1} is the target displacement in the next step, H is the parameter (either 1 or 0) of the testing hold function that enables researchers to observe the responses of the specimen at any time, T represents the parameter (either 1 or 0) of the trigger function, r stands for the ramping rate, and dt refers to the time increment. D_{n+1} is achieved by adding the current displacement (D_n) and the displacement increment ($H \times r \times dt \times T$). With the Switch block, the test can continuously running when H is set at 1. If H is switched to 0, the displacement increment would be zero and the test is on hold. The ramping rate (r) was set at 3mm/sec in this BRB test, but it could be adjustable during the test. The dt is the update period (1/1024 second) of the MATS controller. In Fig. 10, the displacement command is ramped in 1.0 second and then set the T from 1 to 0. When T is set to 0, the displacement command is held for another 2.5 second to allow the trigging and collecting data of the DAQ system. After that, T is set back to 1 and the actuators are ramped to the next target. The axial force versus deformation relationships of the BRB are shown in Fig. 11. The peak axial force was about 3,000kN when axial deformation reached 60mm.

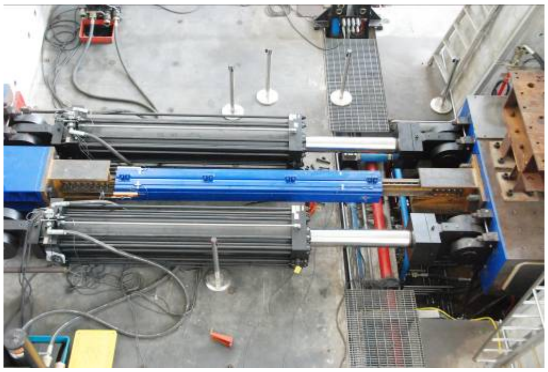

Fig. 7. Test setup for a BRB

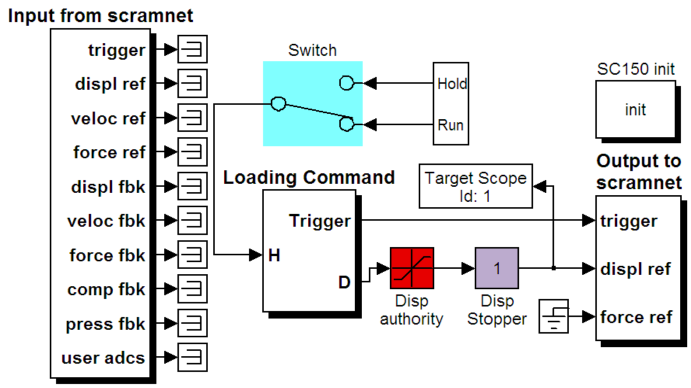

Fig. 8. Loading command model in Simulink

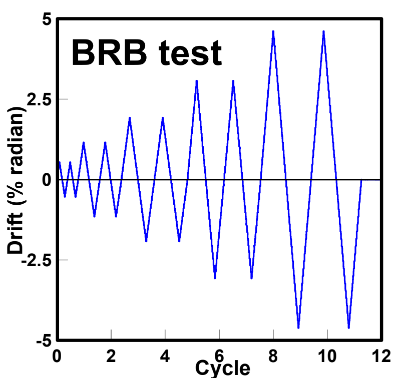

Fig. 9. Loading protocol

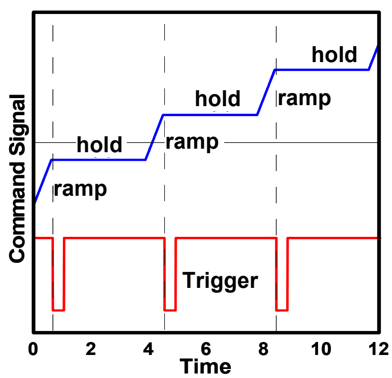

Fig. 10. Test commands

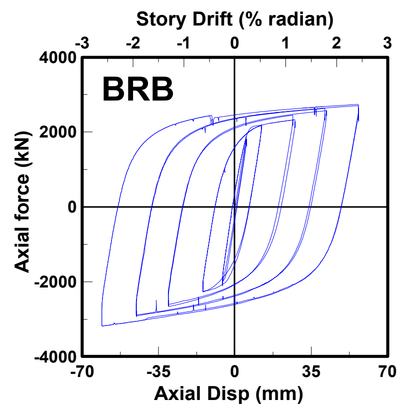

Fig. 11. Force versus deformation relationships of the BRB

C-SPSW:

Illustration of the C-SPSW test. The coupled steel plate shear walls (C-SPSW) were designed for the transverse direction of a six-story prototype building (Tsai and Chang 2009). As illustrated in Fig. 12, one of the C-SPSWs was cut at the third story into a substructure and reduced to a 40% scale specimen. The 0.4-scale bottom two and half stories C-SPSW substructure was installed upside down between the cross beam and the platen. From the free body diagram of the substructure in Fig. 12, the specimen was required to resist the vertical loads, the lateral seismic shear and the overturning moment transmitted from the upper stories of the six-story building. It is hypothesized that the lateral force distribution was an inverted triangular shape and the lateral seismic shear forces at the lowest two floors were ignored. Thus, the overturning moment at the section cut of the specimen was 2.51-meter times of the shear force in the specimen. According to the hydraulic pressure (3000psi) of the MATS, the top two hold-down actuators could only provide 2,800-kN compressive force on the platen. However, the applied overturning moment must not result in any of the bottom dynamic actuators to undergo tension when the lateral displacement of the specimen became large. Hence, there were two additional vertical static actuators as illustrated in Fig. 13 installed between the cross beam and the platen to provide a total of 2,000kN. These two static actuators supplemented the hold-down actuators in balancing the bottom six dynamic actuators.

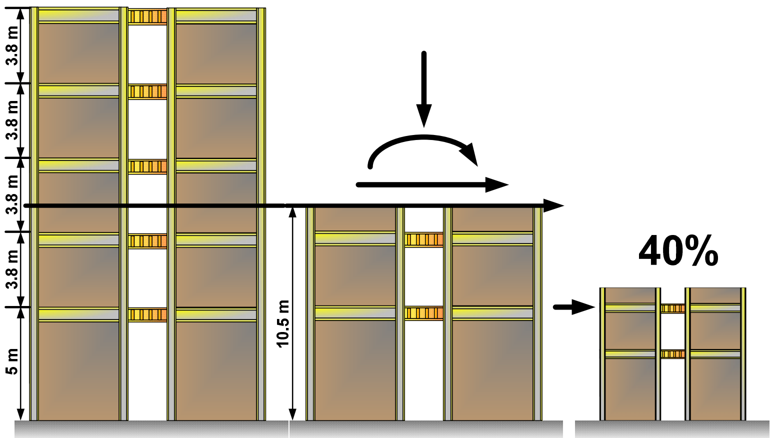

Fig. 12. Illustration of the specimen

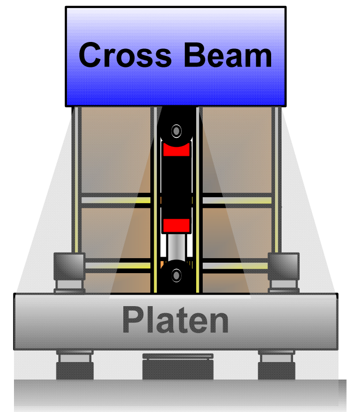

Fig. 13. Test setup of the C-SPSW

Pitch Force Control model of the C-SPSW test. The Loading command block mentioned in the BRB test has been applied in this model to provide shear loading on the specimen as shown in Fig. 14. The details of the Pitch Force Control model are shown in Fig. 15. In the beginning of the test, the manual settings of the actual offsets including the initial values of the pitch force and the pitch displacement are required. That is to avoid the discontinuity of any commands mentioned earlier. When the longitudinal actuators reach any displacement in each step, the pitch force feedback (overturning moment) and the longitudinal displacement feedback were continuously transmitted at a frequency of 1024 Hz to the Target PC through the optical cables. The Pitch Force command is then computed using the longitudinal force feedback. However, this pitch force can not be applied directly. Thus, the required pitch increment (error) calculated from the difference between the pitch force command and feedback would be put into the inner PID controller block. The PID controller block was built to ensure the calculated error was stable. Proportional gain would enlarge the command which would reduce the error immediately, but the high gains could lead to overshoot. Integral gain would provide robust reduction in steady-state errors, but it could make the system less stable. Derivative gain could improve stability when proportional gain is slightly high. In this test, the stable pitch-force increment generated from the PID controller was transformed into the pitch-displacement increment by the Conversion block. Finally, the pitch-displacement target was achieved by adding the offset, current pitch-displacement feedback and the pitch-displacement increment together. In this manner, although the pitch-force target was completed by using a pitch-displacement control loop, it has successfully achieved a force-control command generated from the output of inner PID controller. In this test, the target pitch forces have been well-controlled by applying appropriate PID values. In order to prevent the vertical actuators from damages, the pitch displacement authority was set between +1.5 and -1.5 degree. It should be noted that the Stopper block mentioned before was crucial. This is because at the end of the test, the residual moment of the specimen was about 1,800kN-meter when the loading protocol command returned back to 0-mm. At that instance, the Stopper had to be slowly altered from 100% to 0.0 without sudden drop of pitch displacement before the SCRAMNet control mode was switched off. In this test, two DAQ systems were adopted: one collected less important data at the sampling rate of 0.3Hz per trigger. The other one collected the critical data at the sampling rate of 30Hz per trigger.

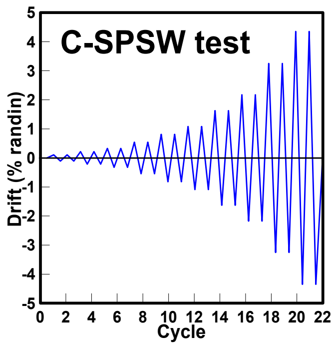

Fig. 14. Loading protocol

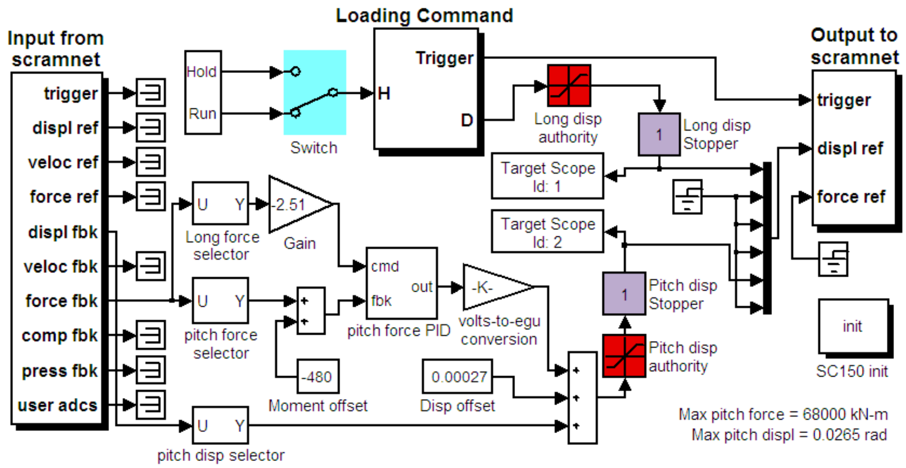

Fig. 15. Pitch Force Control model in Simulink

Experimental results of the C-SPSW. The lateral force versus the lateral displacement or story drift responses of the specimen are shown in Fig. 16. The peak lateral force was less than 1,800kN, which means the required overturning moment applied on the specimen was less than 4,500kN-meter. Figure 17 shows the command and feedback of the pitch force in the first lateral drift cycle obtained from the Recorder function in the MATS Control Panel. The enlarged part in Fig. 17 shows the beginning of each ramp step. It appears that the feedback did not meet the command very well. It suggests that the PID values tuned in the test were somewhat conservative that a better and more precise control would be preferable. However, the feedback has already met the command well enough during the 2.5 seconds hold. In order to avoid uncontrolled situation if the C-SPSW all of a sudden had lost its lateral strength, the conservative PID values adopted herein would be helpful in preventing the system from overshooting. Since the DAQ systems were triggered in the beginning of the 2.5 seconds hold, the data collected by the DAQ systems has confirmed that overturning moment versus shear force relationships agreed with the test requirement very well (Tsai & Chang, 2009). Force relaxation was also observed during the held 2.5 seconds.

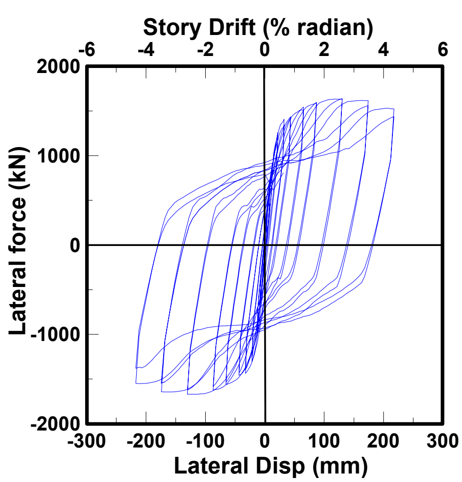

Fig. 16. Force versus deformation relationship of the C-SPSW

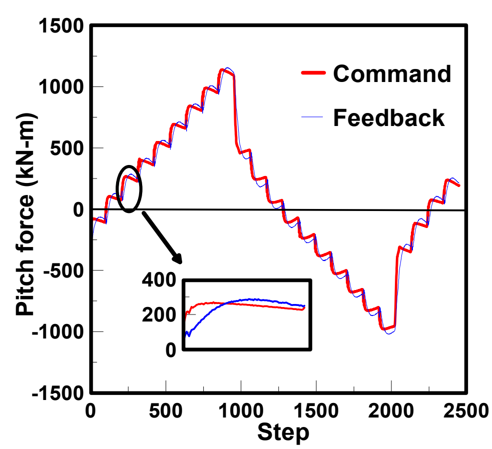

Fig. 17. Command and feedback of the pitch force

CONCLUSIONS

These example experiments on structural components and sub-assemblies confirm the versatility of the MATS. The proposed experimental control technique using SCRAMNet on the MATS has been successful. The Stopper and Offset blocks in Simulink model successfully avoided the sudden forces or displacements to occur in the system when the SCRAMNet function was turned on or off. The control algorithm can be conveniently modified by changing the Simulink models introduced in this paper. Trigger function has been found effective in driving different DAQ systems to collect test data under the same trigger frequency. Technically, the control stability can be further improved by inserting control blocks based on classical or modern control theory. For the C-SPSW test, it appears that this experimental technique could be extended to a more general experimental control framework, such as using the shaking table or other control system for hybrid simulations in NCREE.

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